

PROJECT ADMINISTRATION DATA SHEET

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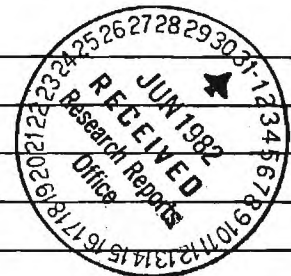
Project No. E-19-602DATE 5/31/82Project Director: Dr. A. P. Yoganathan School/Lab ChESponsor: American Heart Association, Georgia Affiliate, Inc.Atlanta, GA 30324Type Agreement: Grant dated 5/24/82Award Period: From 7/1/82 To 6/30/83 (Performance) 8/1/82 (Reports)Sponsor Amount: \$12,650 Contracted through:Cost Sharing: n/a GTRI/GMXTitle: Fluid Dynamic Studies of Prosthetic Heart ValvesADMINISTRATIVE DATAOCA Contact Linda H. Bowman x4820

1) Sponsor Technical Contact:

2) Sponsor Admin/Contractual Matters:

Ms. Ann AngeloProgram DirectorAmerican Heart Assoc. GeorgiaAffiliate; 2581 Piedmont Rd., N.E.Box 13589Atlanta, GA 30324404-261-2260Defense Priority Rating: noneSecurity Classification: noneRESTRICTIONSSee Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval -- Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of \$500 or 125% of approved proposal budget category.

Equipment: Title vests with GITCOMMENTS:COPIES TO:Administrative Coordinator
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SPONSORED PROJECT TERMINATION SHEETDate August 18, 1983

Project Title: "Fluid Dynamic Studies of Prosthetic Heart Valves"

Project No: E-19-602

Project Director: Dr. A. P. Yoganathan

Sponsor: American Heart Association; Georgia Affiliate, Inc.

Effective Termination Date: 6-30-83Clearance of Accounting Charges: 8-1-83

Grant/Contract Closeout Actions Remaining:

- ☐ Final Invoice and Closing Documents
- ☒ Final Fiscal Report - on forms provided by Georgia Heart Association
- ☒ Final Report of Inventions
- ☒ ~~EES~~ Property Inventory & Related Certificate
- ☐ Classified Material Certificate
- ☐ Other _____

Assigned to: Chemical Engineering (School/~~laboratory~~)COPIES TO:

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AMERICAN HEART ASSOCIATION - GEORGIA AFFILIATE
FLUID DYNAMIC STUDIES OF PROSTHETIC HEART VALVES
(GRANT-IN-AID)
FINAL REPORT (7/1/82 - 6/30/83)

I. Principal Investigator: Professor Ajit P. Yoganathan, Ph.D.,
Georgia Tech

Collaborator: R. H. Franch, M.D.
Emory University Medical School

II. Project Report

(a) Even after 20 years of experience the problems associated with valve prostheses have not been totally eliminated. Some of these important problems, such as thrombus formation, hemolysis, tissue overgrowth and damage to the endothelial lining of the vessel wall adjacent to the valve are directly related to the fluid dynamics associated with the various valves. Detailed in vitro fluid dynamic studies of bioprostheses, the newest designs of mechanical and polymeric heart valves, and valve conduits are being conducted. The in vitro laboratory data will be correlated with clinical and pathologic observations. It is hoped that the results of this research will lead to better and longer lasting heart valve prostheses and related cardiovascular products.

The major portion of the project effort during the past year was spent in conducting detailed pulsatile flow velocity and shear stress measurements with various valve designs, in both aortic and mitral flow chambers. Such measurements are virtually non-existent in the literature, and are extremely important if we are to understand the fundamental fluid dynamic (hemodynamic) characteristics of prosthetic heart valves. The following size 27 mm valves were studied: Starr-Edwards (1260) ball valve, Bjork-Shiley (CC-C) tilting disc valve, Medtronic-Hall tilting disc valve, St. Jude bi-leaflet valve, Beall (106) disc valve, Ionescu-Shiley pericardial valve, and Hancock (standard and modified orifice) porcine valves. All studies were conducted under physiologic conditions in the Georgia Tech pulse duplicator system, at cardiac outputs of 5 to 6 l/min, using a three beam (two dimensional) laser Doppler anemometer system. Examples of some of the results obtained are given below in brief format:

Previous experience has shown that the flow fields and the shear stress fields near the valves provide the most valuable information. Therefore, half profiles were taken as close as possible to the valve superstructure, and full profiles were obtained a little further downstream. Due to the nature of the 3 beam system, the measurements could not be made as close as those made using a 2 beam system. Therefore, the downstream location where the profiles were taken were different from valve to valve. For some valves, such as the Starr-Edwards and Ionescu-Shiley, the velocity and sheer stress profiles were taken relatively far away from the valve sewing ring, because of the high profiles of these prostheses. Measurements were made at locations where the flow field was thought to be most turbulent or where regions of flow separation and/or stagnation were expected. The highest measured root mean square fluctuating component of the axial velocity (rms) is also provided in the text for each valve. For valves which produced a sharp jet type flow, such

as the Ionescu-Shiley, the turbulent shear stress also had a steep rise within a very short radial distance. Hence, the highest turbulent shear stress measured could be lower than the highest turbulent shear stress actually existing in the flow channel. The wall shear stress was also strongly dependent upon the location where the measurements were made. Wall shear stresses higher than the measured values could have existed at certain locations where measurements were not made. However, measurements were made at locations where the wall shear stresses were thought to be the highest. The wall shear stresses for the mechanical valves were calculated based on the viscosity of the water-glycerine (blood analog) solution (3.5 cp). For the tissue valves, experiments were conducted in saline solution. However, the wall shear stresses were also calculated based on a viscosity of 3.5 cp.

(i) Starr-Edwards Aortic Caged Ball Valve

The forward flow formed a circumferential jet along the wall of the flow channel. The flow in the annular region was jet like. A large wake was observed distal to the ball, which was a result of flow separation from the surface of the ball. The closest downstream measurement was taken 26 mm downstream of the sewing ring, since the valve cage itself extended 20 mm downstream of the sewing ring. The highest velocity occurred 30 mm downstream of the valve, which had the value of 183.2 cm/s. The highest shear stress observed was 1861 dynes/cm^2 , 30 mm downstream of the valve. The rms value at this point was 65 cm/s, which was also the highest rms value observed. Back scatter measurements in the annular region under steady flow conditions at a flow rate of 25 l/min, indicated that the highest turbulent shear stress was 2900 dynes/cm^2 . Therefore, the highest turbulent shear stress in this region under pulsatile flow

conditions would be expected to be in the range of 3000-5000 dynes/cm². The turbulent shear stress was elevated on the centerline throughout the entire cycle in the whole flow channel. The average value was about 700 dynes/cm². Off centerline, it was even more elevated with an average value of 900 dynes/cm². The velocity profiles showed that the flow field at peak systole and during the deceleration phase did not change much from 26 to 30 mm downstream of the valve. The flow in the acceleration phase was more evenly distributed at 30 mm than that at 26 mm downstream of the valve. Reverse flow was observed in the central part of the flow channel on the centerline at peak systole and during the deceleration phase. The highest negative velocity was -22.1 cm/s. No reverse flow was observed during the acceleration phase. A region of stagnation about 5 mm in diameter would be expected distal to the cage apex. The off centerline (6.25 mm above centerline) profiles showed a stagnation region in the central part of the flow channel during the deceleration phase. No reverse velocity was measured, which means that the wake had a radius of less than 6.25 mm.

The highest (estimated) wall shear stress measured was 1940 dynes/cm², 22 mm downstream of the valve. The measurement upstream of the valve 60 ms after the end of the systole showed the closure back flow of the valve. The leakage back flow of this valve was negligible.

(ii) Bjork-Shiley Aortic Tilting Disc Valve

The flow field produced by this valve was not symmetric. Two high velocity jets were observed, one from the major orifice, and the other from the minor orifice. A low velocity region (relatively stagnant), about 5 mm in width, existed between the major and minor orifice jets at all three cardiac cycle times at which velocity

measurements were made. The major orifice jet was wider than the minor orifice jet. The highest velocity and turbulent shear stresses measured in the major and minor orifices were about the same, 210 cm/s, and 1800 dynes/cm², respectively. Regions of flow separation could be observed in the major and minor orifices, and the region of flow separation in the minor orifice was larger than that in the major orifice. The largest region of separation was observed 11 mm downstream of the valve in the minor orifice region with reverse velocities extending 7 mm from the wall. Narrow high velocity jets were observed in the minor orifice, beneath the occluder, and adjacent to the flow channel walls. Regions of flow separation (or stagnation) existed next to these jets. The highest shear stress observed was 3363 dynes/cm², 7 mm downstream of the valve, on the centerline. This was in the region between the major and minor orifice jets. The obstruction of the occluder was the reason for this elevated turbulent shear stress. The average turbulent shear stress over this region at peak systole was about 1600 dynes/cm². The turbulence decayed very rapidly in the major orifice, as the flow travelled downstream. In the minor orifice, the turbulent shear stress did not seem to change, especially at peak systole and during the deceleration phase. The high turbulent shear stress region was more spread out and also tended to persist longer in the minor orifice than in the major orifice. This indicated that the flow was more disturbed in the minor orifice region.

The highest rms value measured was 68.1 cm/s, at the same location that the highest shear stress was measured. The highest leakage back flow was observed next to the flow channel wall, directly upstream from the space between the occluder and the orifice ring, with a negative velocity as high as -22 cm/s, which caused an elevated shear stress of 430 dynes/cm².

The highest (estimated) wall shear stress measured was 1380 dynes/cm^2 , 26 mm downstream of the valve in the major orifice, roughly the position where the major orifice jet hit the wall.

(iii) St. Jude Aortic Bileaflet Valve

The major part of the forward flow emerged from the side orifices of the valve. The highest velocity measured in the side orifice was 218 cm/s, while in the center orifice it was 223 cm/s. The highest turbulent shear stress in the side orifice was 1780 dynes/cm^2 and the rms value at this location was also the highest, with a value of 52 cm/s. The high turbulent shear stress could be related to the asynchronous opening of the valve leaflets. The highest turbulent shear stress in the center orifice was 1700 dynes/cm^2 , with an rms value of 53 cm/s. The 90 degree rotated profile at peak systole showed an average shear stress over the entire flow channel of about 1200 dynes/cm^2 . The velocity profiles showed two dips due to the presence of the leaflets, which also led to high turbulent shear stresses. The region of forward flow narrowed down as the flow travelled downstream. Flow separated from the orifice and sewing rings of the valve. The region of reversed flow along the centerline, grew from 3 mm from the wall 8 mm downstream of the valve, to 5 mm from the wall 13 mm downstream of the valve, during the deceleration phase. The region of flow separation, 6.25 mm above the centerline, was larger than that on the centerline. The highest reverse velocity measured in the region of separation was -28 cm/s. Leakage back flow was measured upstream of the central pivot of the valve during diastole with a negative velocity of -16 cm/s (highest value), and a turbulent shear stress of 325 dynes/cm^2 . The highest estimated wall shear stress was 630 dynes/cm^2 .

(iv) Hancock Modified Orifice Aortic Porcine Xenograft

This valve also produced a high velocity jet. The velocity profiles showed that the jet was relatively symmetric 10 mm downstream of the valve, and not as symmetric 15 mm downstream of the valve. This indicated that the fluid did not flow axially. The velocity profiles showed a dip in the center of the jet. The highest velocity and turbulent shear stress measured were 335 cm/s and 3075 dynes/cm², respectively, 10 mm downstream of the valve. The off centerline profiles showed no significant change in the velocity and turbulent shear stress from the centerline profiles, at peak systole. The high turbulent shear stresses were confined to a narrow region around the jet. The peak velocity of the jet decreased to 180 cm/s as it moved from 10 to 15 mm downstream of the valve. Although the peak turbulent shear stress also decreased to 2450 dynes/cm², the turbulence did not decay very rapidly. Flow separated from the downstream edge of the leaflets. The region between the jet and the wall was relatively stagnant, and no high velocity reversed flow was measured. This implied that the region between the outflow surfaces of the leaflets and the wall was stagnant. The highest rms value measured was 74 cm/s. The highest estimated wall shear stress was 490 dynes/cm², 63 mm downstream of the valve. No leakage back flow was observed.

(v) Beall Mitral Caged Disc Valve

This valve produced a circumferential jet, which narrowed down as it travelled from 11 to 17 mm downstream of the valve. The closest profile was taken 11 mm downstream of the valve, which was 3 mm downstream of the fully opened occluder. The velocity of the jet increased as the jet narrowed. The highest velocity measured was 113 cm/s, 17 mm downstream of the valve. The highest shear stress measured was 1926 dynes/cm²,

also 11 mm downstream of the valve. The rms value at this measuring point was 65 cm/s, which was also the highest rms value measured. Only very narrow regions of high turbulent shear stress existed on the edge of the jet. The turbulent shear stress decayed very rapidly from 11 to 17 mm downstream of the valve. The high turbulent shear stress was only 688 dynes/cm², 17 mm downstream of the valve. A large wake existed downstream of the occluder, which was the result of boundary layer separation from the edge of the occluder. A high negative velocity was measured in the wake at peak diastole and during the deceleration phase. During the acceleration phase, this region was relatively stagnant. The highest negative velocity was -31 cm/s, during the deceleration phase, 17 mm downstream of the valve. The turbulent shear stresses and rms values in the wake region were almost zero. The highest estimated wall shear stress was 1780 dynes/cm², 25 mm downstream of the valve. The leakage back flow of this valve was negligible.

(vi) Medtronic-Hall Mitral Tilting Disc Valve

These results were very different from those obtained in the aortic position. Most of the forward flow emerged from the major orifice of the valve. The highest turbulent shear stress measured in the major orifice was 2591 dynes/cm², 18 mm downstream of the valve. The occluder was oscillating during diastole, which could have led to the shedding of vortices downstream and caused high turbulent shear stresses. This phenomena was not observed in the aortic position. The highest velocity was 105 cm/s, at the same downstream location in the major orifice. The highest velocity in the minor orifice occurred beneath the occluder, 18 mm downstream of the valve, and was 97 cm/s. The forward flow was confined in a very narrow region in the minor orifice. The highest

turbulent shear stress in the minor orifice was 1800 dynes/cm^2 , 8 mm downstream of the valve. The highest rms values were 54 cm/s and 45 cm/s, in the major and minor orifices, respectively. The largest region of flow separation existed in the minor orifice, which extended 18 mm from the wall. Flow separation in the major orifice existed only at peak diastole, and extended only 5 mm from the wall. The profile downstream of the 90 degree rotated valve showed that the flow separated from the stent in the minor orifice. The highest (estimated) wall shear stress measured was 480 dynes/cm^2 , 59 mm downstream of the valve. The upstream velocity profiles showed that the back flow occurred in the center of the flow channel, through the hole in the occluder. The highest turbulent shear stress measured at this location was 713 dynes/cm^2 .

(vii) St. Jude Miral Bileaflet Valve

The velocity profiles had three peaks; one from the center orifice, and two from the side orifices. The highest velocity was 103 cm/s in the side orifices. The highest turbulent shear stress, in the side orifices, was 574 dynes/cm^2 , 19 mm downstream of the valve, and 10 mm above centerline. The rms value at this point was 28 cm/s. The highest turbulent shear stress in the center orifice was 760 dynes/cm^2 . Flow separated from either side of the orifice and the sewing ring of the valve. The largest region of flow separation existed 12 mm downstream of the valve, in the center orifice, which extended 15 mm from the wall. The two leaflets of the valve did not open at the same time. The effect was not obvious on the centerline of the flow channel, but from the off-centerline velocity profile during the acceleration phase, this phenomenon was clearly observed. The highest (estimated) wall shear stress measured was 200 dynes/cm^2 , 50 mm downstream of the valve. During systole, back flow existed in the center part of the flow channel, with a reverse velocity as high as -17 cm/s, which led to a turbulent shear stress of 117 dynes/cm^2 .

(viii) Hancock (Std) Mitral Porcine Xenograft

This valve produced a high velocity jet. The jet was confined to a narrow region which was not in the center of the flow channel, but a little bit shifted to one side. The highest velocity measured was 216 cm/s, 17 mm downstream of the valve. The highest shear stress measured was 1947 dynes/cm^2 , and the highest rms value was 62 cm/s, 10 mm downstream of the valve, and 10 mm below the center line. The high turbulent shear stresses were confined to a narrow region around the jet. The measurements showed that the flow field did not change much from 10 to 17 mm downstream of the valve. The peak velocity decreased to 165 cm/s when measured 10 mm below the centerline. The jet narrowed, and a dip showed up in the central part of the velocity profile, which caused high turbulent shear stresses. Flow separated from the downstream edge of the leaflets. The region around the jet appeared to be relatively stagnant; no high velocity reverse flow was measured. This implied the region behind the leaflets was stagnant. The highest (estimated) wall shear stress measured was 260 dynes/cm^2 , 63 mm downstream of the valve.

(ix) Ionescu-Shiley Mitral Pericardial Xenograft

A high velocity jet was produced by this valve, which occupied a narrow region in the central part of the flow channel. The velocity profiles during the acceleration phase showed a dip in the center, which still could be seen at peak diastole. The jet had about the same velocity 21 and 27 mm downstream of the valve. The highest velocity measured was 191 cm/s, 27 mm downstream of the valve. The highest shear stress measured was 1376 dynes/cm^2 , and the highest rms value was 46 cm/s, 27 mm downstream of the sewing ring. The high turbulent shear stresses were confined to a narrow region around the jet. Flow separated from the

downstream edge of the leaflets. The region around the jet was stagnant, and extended about 17 mm from the wall. This implied the region behind the leaflets was stagnant. The highest estimated wall shear stress measured was 320 dynes/cm^2 . The measurement upstream of the valve during diastole, showed that the back flow occurred in the center of the flow channel, which was caused by the closing movement of the valve leaflets.

The turbulent shear stresses measured downstream of all the valve designs studied are large enough to cause sub-leathal and/or leathal damage to red-cells and platelets. Wall shear stresses larger than 400 to 600 dynes/cm^2 could cause damage to the endothelial tissue of the vessel or chamber walls. Furthermore, the regions of flow stagnation and flow separation observed adjacent to the various valve designs, correlate well with locations of thrombus formation and excess tissue overgrowth observed on recovered valves of the same designs.

During the year we also examined and studied Beall, Starr-Edwards, Kay-Shiley, Bjork-Shiley, St. Jude and Porcine heart valves, recovered at surgery and/or autopsy. Pathologic studies of the mechanical and tissue valves showed that the locations of thrombus formation and excess fibrotic tissue growth correlated well with the in vitro flow patterns of the various valve designs. The recovered valves were also studied in the Georgia Tech pulse duplicator under appropriate physiologic conditions to evaluate their fluid dynamic (hemodynamic) characteristics. The obtained in vitro results correlated quite well with the available clinical information and data. An interesting example of one of the studies conducted is given below:

Three Beall valves with Teflon discs recovered from patients undergoing surgery at Emory University Hospital, were evaluated for their regurgitation characteristics on the Georgia Tech pulse duplicator system.

All three discs had varying degrees of notching and wear marks. In one case the disc had been notched and worn to such an extent that it had escaped from the valve cage. The disc was, however, recovered from the patient's descending thoracic aorta. All three valves were tested in the mitral position under the following conditions: (i) heart rate of 70 min, (ii) systolic time of 300 ms, (iii) mean aortic pressure of 90 - 100 mm Hg, and (iv) cardiac output in the range of 2.0 to 7.5 l/min. In addition, the opening and closing motions of the discs were observed and photographed with a SLR camera. In the case of the valve with the escaped disc, a high-speed (200 frames/sec) 16 mm movie was made of the disc motion.

Due to the notching and wear marks on their respective discs, all three valves were excessively regurgitant as shown by the results in Table 1. In addition, the discs showed improper and unpredictable movement within their valve cages. Under certain conditions the Teflon discs cocked both in the open and/or closed positions. The cocking of the discs in the closed positions led to severe regurgitation. All three valves were removed at surgery, due to clinical manifestations of varying degrees of regurgitation. The improper disc motions are shown very clearly in the 16 mm high speed movie film. In this particular case, the opening characteristics depict the disc in a "floating" type motion. The film also clearly shows the disc opening and closing in cocked positions, and the variations in the opening and closing motions from cycle to cycle.

Table 1: Regurgitant Volumes for the Beall Valves

Valve #	Cardiac Output l/min	Total Regurgitant Volume* ml/beat
1	7.4	16.2
1	5.3	14.1 - 43.1
1	2.1	36.4
2+	5.5	51.0
2+	3.8	35.3
2+	2.0	45.7
3	8.2	22.3
3	5.1	37.6
3	4.0	59.1
3	3.5	47.0

* closure plus leakage volumes

+ valve with escaped disc

(b) Lay Summary

The research is mainly directed toward understanding the fluid dynamic performances of different designs of prosthetic heart valves. In order to evaluate the performances pressure drop, regurgitation, and velocity and shear stress measurements are being conducted in a flow system which duplicates the pulsating flow of the heart. Using sophisticated laser beam techniques, velocity and shear fields are measured in the immediate vicinity of the valves. By knowing the shear and velocity fields, valves can be appropriately designed to minimize damage to the cellular components of blood and to minimize the opportunity for excess tissue growth on and around valve prostheses. The pressure gradient and regurgitant characteristics are two of the major determinants in the clinical use of a given valve design. The overall importance of our research efforts is to understand the advantages and disadvantages of current prosthetic heart valves, so that better and longer lasting valves may be developed. This in turn would be beneficial to the many patients who suffer from valvular heart disease.

III. Collaborators

(a) During the three year duration of the project the research group at Georgia Tech has interacted on a continuing and very productive basis with R. H. Franch, M.D., cardiologist at Emory University Hospital. We have also interacted extensively with E. C. Harrison, M.D., cardiologist at LA County - USC Medical Center (Los Angeles) and A. Chaux, M.D., cardiovascular surgeon at Cedars-Sinai Medical Center (Los Angeles). All three have been very helpful in obtaining clinical data on a variety of valve patients and in examining heart valves recovered during surgery and/or autopsy.

(b) The following graduate students at Georgia Tech have worked on the project:

Yi-Ren Woo	--	Ph.D. Student
Dana Stevenson	--	Ph.D. Student
Patrick Faughnan	--	M.S. Student
Kelly McCarty	--	Undergraduate Student

IV. Publications

(a) Abstracts and Presentations

1. Woo, Y-R, Williams, F. P., and Yoganathan, A.P., "In vitro fluid dynamics characteristics of the Applied Biomedical trileaflet valve prosthesis," Proceedings of the 3rd International Conference on Mechanics in Medicine and Biology, pp. 235-236, Compiègne, France, July 1982.
2. Yoganathan, A. P., Harrison, E. C., and Franch, R. H. "Clinical pathologic problems observed with prosthetic heart valves: Possible relationship to fluid dynamics," Proceedings of the 3rd International Conference on Mechanics in Medicine and Biology, pp. 201-202, Compiègne, France, July 1982.
3. Yoganathan, A. P. and Franch, R. H., "Hemodynamic characteristics of current prosthetic heart valves," Proceedings of the Scientific Sessions American Heart Association - Georgia Affiliate, pp. 21, Pine Mountain, GA, October 1982.
4. Yoganathan, A. P., Franch, R. H., and Harrison, E. C., "Clinical pathologic problems observed with prosthetic heart valves: Possible relationship to fluid dynamics," Proceedings of the Scientific Sessions American Heart Association - Georgia Affiliate, pp. 22, Pine Mountain, GA, October 1982.
5. Yoganathan, A. P., "Current status of prosthetic heart valves," Proceedings of the Division of Organic Coatings and Applied Polymer Science, ACS, Vol. 48, pp. 632-638, Seattle, WA, March 1983.
6. Hanle, D. D., Harrison, E. C., Corcoran, W. H., and Yoganathan, A. P., "The measurement of the three dimensional velocity fields downstream of artificial aortic heart valves in vitro using laser-Doppler anemometry," Proceedings of the Joint ASME/ASCE Mechanics Conference, Houston, TX, June 1983.
7. Yoganathan, A.P., "In Vitro Hemodynamics of the St. Jude Bi-leaflet Heart Valve Prosthesis," 3rd International Symposium on the St. Jude Medical Heart Valve, Scottsdale, AZ, November 1982.

(b) Manuscripts

1. Yoganathan, A. P., Stevenson, D. M., Williams, F. P., Woo, Y-R., Franch, R. H., and Harrison, E. C., "In vitro fluid dynamic characteristics of the Medtronic-Hall pivoting disc heart valve prosthesis," accepted for publication in Scandinavian Journal of Thoracic and Cardiovascular Surgery, Vol. 16, pp. 235-243, 1982.
2. Yoganathan, A. P., Woo, Y-R., Williams, F. P., Stevenson, D. M., Franch, R. H., and Harrison, E. C., "In vitro fluid dynamic characteristics of Ionescu-Shiley and Carpentier-Edwards tissue bioprostheses," accepted for publication in Artificial Organs, August 1982.
3. Woo, Y-R, Williams, F. P., and Yoganathan, A. P., "In vitro fluid dynamic characteristics of a trileaflet valve prosthesis," accepted for publication in Scandinavian Journal of Thoracic and Cardiovascular Surgery, January 1983.
4. Yoganathan, A. P., Stevenson, D. M., Woo, Y-R, and Strand, D. M., "An on-line method for evaluating the in vitro pulsatile pressure drop and regurgitant characteristics of prosthetic heart valves," accepted for publication in Medical Instrumentation, March 1983.
5. Woo, Y-R, Williams, F. P., and Yoganathan, A. P., "In Vitro fluid dynamic characteristics of the Abiomed trileaflet valve prosthesis," accepted for publication in Journal of Biomechanical Engineering, March 1983.
6. Yoganathan, A. P., Woo, Y-R, Williams, F. P., Chaux, A., Gray, R. J., and Matloff, J. M., "Tilting disc and porcine aortic valve substitutes: in vitro hydrodynamic characteristics," accepted for publication in American Journal of Cardiology, June 1983.
7. Chaux, A., Gray, R. J., Matloff, J. M., and Yoganathan, A. P., "Tilting disc and porcine aortic valve substitutes: in vivo hydrodynamic characteristics," submitted to American Journal of Cardiology, April 1983.
8. Yoganathan, A. P., Chaux, A., Gray, R. J., De Robertis, M., and Matloff, J. M., "Flow Characteristics of the St. Jude prosthetic valve: an in vitro and in vivo study," Artificial Organs, Vol. 6, pp. 288-294, 1982.